STATUS OF THE FERMILAB TEVATRON PROJECT

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SUMMARY

A brief survey of the Fermilab Tevatron is presented, with emphasis on the magnet development. Some operational aspects of strings of up to 24 magnets are presented.

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*A great many individuals under the direction of R.R.Wilson have contributed enormously to this project. Recognition of some of these contributions is given by means of references -- others are presumably having their deeds recorded by Abou Ben Adhem and will be rewarded at an appropriate time and place.

The Energy Doubler is a proton accelerator that receives its injected beam from the Fermilab Main Ring at 150 GeV and is capable of accelerating the beam to 1000 GeV. Fixed target physics as well as colliding beam experiments are planned and both slow (few seconds) and fast extraction (~1 msec) are planned at intensities of 2×10^{13} protons per pulse.[1]

In the ring there are 760 dipoles and 240 quadrupoles. These elements, consisting of four dipoles and one quadrupole per half cell, are all connected in series and operate at a current of about 4500 A. The field in the dipoles is near 4.5 T and the quads have a gradient of about 20 kG/inch.

The magnets are powered by six 2 kV supplies distributed around the ring that are capable of generating a 75 GeV/sec ramp rate.[2] At flat top a single very well regulated low voltage, low ripple, holding supply will maintain the current during extraction or colliding beam experiments.

Since at full field each magnet stores almost 0.5 MJ, it is obvious that a sophisticated protection system is necessary to protect the magnets during a quench of any one of them. The system planned,[2] uses a micro-processor to monitor the voltage across each half cell and compares it with all the others. In the event of a quench the increasing resistive drop is detected and identified as a quench condition. That half-cell is then shorted and internal heaters fired to drive the four magnets normal as quickly as possible. The energy is absorbed in the cold part of the magnet structure, which increases its temperature to less than 150°K and the energy in the rest of the ring is dumped into resistors.

The refrigeration system[3] consists of a very large Central Helium

Liquefier Plant and 24 satellite stations placed around the ring. The

Central Plant is capable of producing up to 5000 ℓ/hr of liquid helium.

In normal operation each satellite is supplied with 92 ℓ/hr and acts

as an amplifier to produce 966 watts of cooling at 4.2°K. Each satel-

lite feeds a string of about 32 dipoles and 8 quads. The satellites

in a stand-alone mode are capable of maintaining the ring supercon-

ducting in case of failure of the Central Plant.

PRESENT STATUS

The Tevatron will be the first large high energy accelerator

employing superconducting technology. Not only is it planned as an

accelerator, but also it will be used as a storage ring. This is an

exceedingly ambitious project with no antecedents for guidance and

consequently we have concentrated our efforts on answering as many of

the new and fundamental problems as possible. So far the following

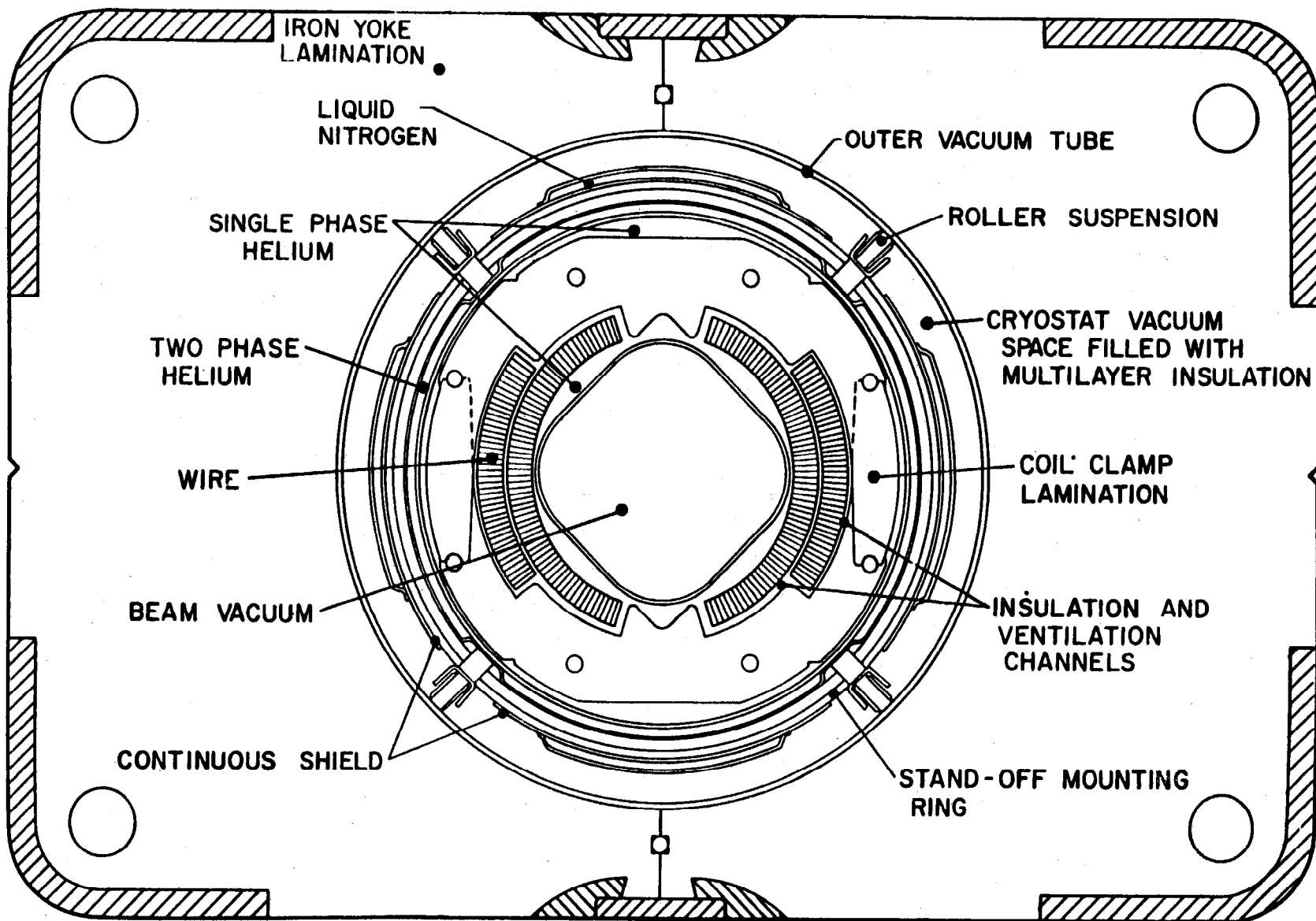five areas have mainly occupied our attention:

1. Methods to fabricate magnets

2. Measurement of the magnet characteristics

3. Behavior of strings of magnets both from a cryogenic

   point as well as protection under quench conditions

4. Effect of high energy protons striking the superconducting

   coils

5. Development of the necessary cryogenic plant.

We address some of these areas here.

1. Magnet Fabrication

The magnet[4] consists of two shells (see Figure 1). The inner

subtends a half angle of ~72° and the outer ~36°. The wire is trap-

ezoidal with dimensions of .307" wide, inside height .045" and outside

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IRON YOKE LAMINATION

LIQUID NITROGEN

OUTER VACUUM TUBE

SINGLE PHASE HELIUM

ROLLER SUSPENSION

CRYOSTAT VACUUM SPACE FILLED WITH MULTILAYER INSULATION

TWO PHASE HELIUM

WIRE

COIL CLAMP LAMINATION

BEAM VACUUM

INSULATION AND VENTILATION CHANNELS

CONTINUOUS SHIELD

STAND-OFF MOUNTING RING

Figure 1. Magnet Cross Section

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TM-880

height .056". It will carry >5300 A of 5 T, and is insulated by a double overlap wrap of 1 mil Kapton and a spiral wrap of B-staged glass tape.

The inner half-coil of 35 turns is wound flat and pressed into shape in a 3000 ton, 24' long precision press. The cross section of the mold is controlled by constructing it from precision stamped laminations.

The outer half-coil of 21 turns is wound over the inner one, using it as a mandrel. This whole structure is again placed in a precision mold, pressed into shape with a second 3000 ton press and cured to its final shape at about 240°F (see Figure 2).
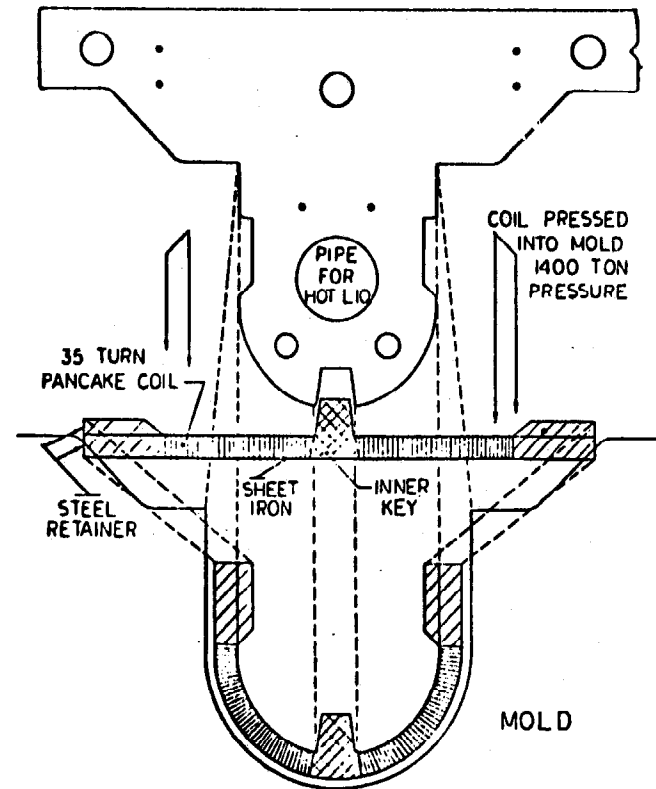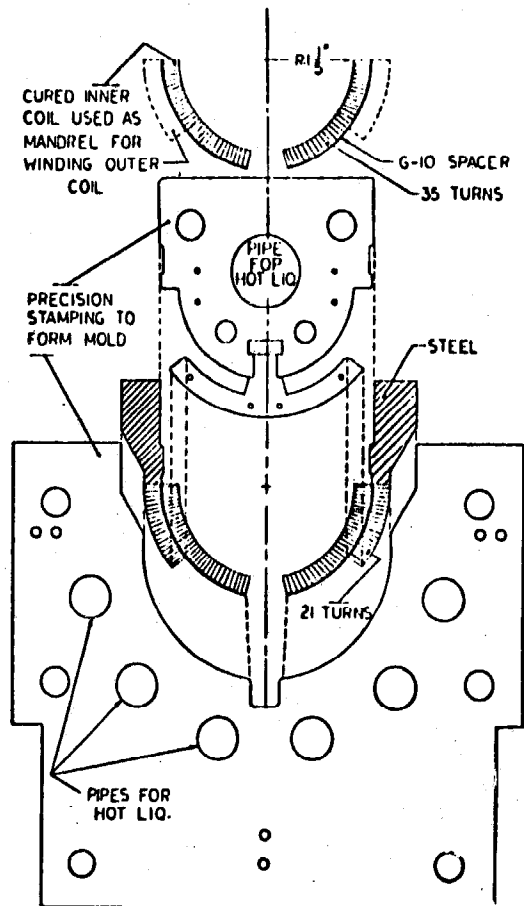
After the half coils are molded, they are measured for circumferential length with a gauge that can apply pressure up to 2000 lb/linear inch on either the inner or outer coil. The size at 1500 lb/linear inch is measured at 10 places along the axis and on each side of the coils. The average of these 10 readings can be controlled to about ±2 mils. Magnet #172 had measurements as given below:

Magnet 172 Coil Sizes

	Inner		Outer	
	Right	Left	Right	Left
Top	2.117±.002	2.117±.002	1.272±.002	1.272±.002
Bottom	2.115±.0015	2.116±.002	1.273±.003	1.2725±.002

The error is the rms fluctuation of the 10 measurements. It is very important to control the size of the coil halves very accurately or when the coil is collared the median plane will not be centered and a quadrupole moment will arise. For instance, a shift of the median plane of .001" of the two coils relative to the fixed corners in the collars will generate a skew quadrupole, a_1, of 2×10^{-4} inches^{-1}.

CURED INNER COIL USED AS MANDREL FOR WINDING OUTER COIL

R1½"

G-10 SPACER

35 TURNS

PIPE FOR HOT LIQ

PRECISION STAMPING TO FORM MOLD

STEEL

21 TURNS

PIPES FOR HOT LIQ.

COIL PRESSED INTO MOLD 1400 TON PRESSURE

PIPE FOR HOT LIQ

35 TURN PANCAKE COIL

SHEET IRON

INNER KEY

STEEL RETAINER

MOLD

Figure 2. Coil Mold Laminations

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A second reason that the coils must be accurately sized is that the "preload" on the coils when collared must be carefully controlled. In order that the coils not move away from the key surfaces in the collar, it is necessary to compress the inner coils with an elastic force of 1300 lb/inch and the outers with 500 lb/inch. However, when the coils are cooled, they shrink more than the collars. The stress-strain curve for the coils, both warm and cold, has been studied[5] and it is found that an initial room temperature compression of the outer coils of 1500 lb/inch and the inners by 4000 lb/inch is necessary in order to achieve the required preload when the coil is cold. These compressions give a differential Young's modulus for the coils of about $10^6(psi)^{-1}$.

The control of coil size is crucial to understand, and additional techniques are still being developed to improve and simplify the accurate fabrication of coils.

After the magnet is collared, the field in the horizontal plane is measured at room temperature.[6] This is done by inserting into the magnet bore a set of 12 long loops 0.195" wide × 24' long, spaced .215" ₵ to ₵. The coils are supported in a stainless steel tray and cast into epoxy for stability. The magnet is then excited at 11 Hz with a current of about 10 A and a lock-in amplifier used to measure the difference of the induced voltages between adjacent loops. This gives a number proportional to the gradient of the field. The coil must be calibrated since differences in area are much greater than the change in B over the aperture ($\delta B/B$ ~10^{-4}). We have been able to refine these measurements sufficiently so that we can determine b_1, b_2, b_3, b_4. These parameters as measured at room temperature without an iron yoke can be related to their final value with a yoke and with the

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coil superconducting.

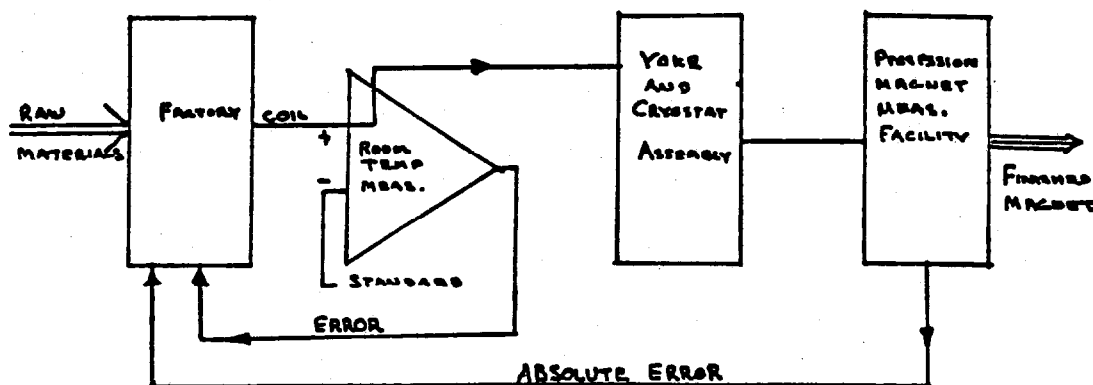The block diagram of the factory then can be outlined as in Figure 3.

Figure 3. Block Diagram of Factory

The room temperature measurements provide a means for immediately monitoring the quality of the collared coil.

If deviations outside of acceptable limits occur in a coil, it can be set aside for recollaring, and appropriate adjustments made in the next coil to correct the trouble. The long-term stability of the system is controlled by a slow feed-back loop provided by the precision magnet test facility.

Two very important points are implicit in the operation of this scheme. First, the factory must make reproducible coils. Fluctuations from coil to coil cannot be removed by the fast feed-back loop. The reproducibility is controlled by the very precise tooling used in the manufacture. It was necessary to invent the "laminated tooling" in order to achieve the necessary small tolerances.[4]

The second important discovery came when it was realized that absolute dimensional accuracy is not required anymore. Consider a

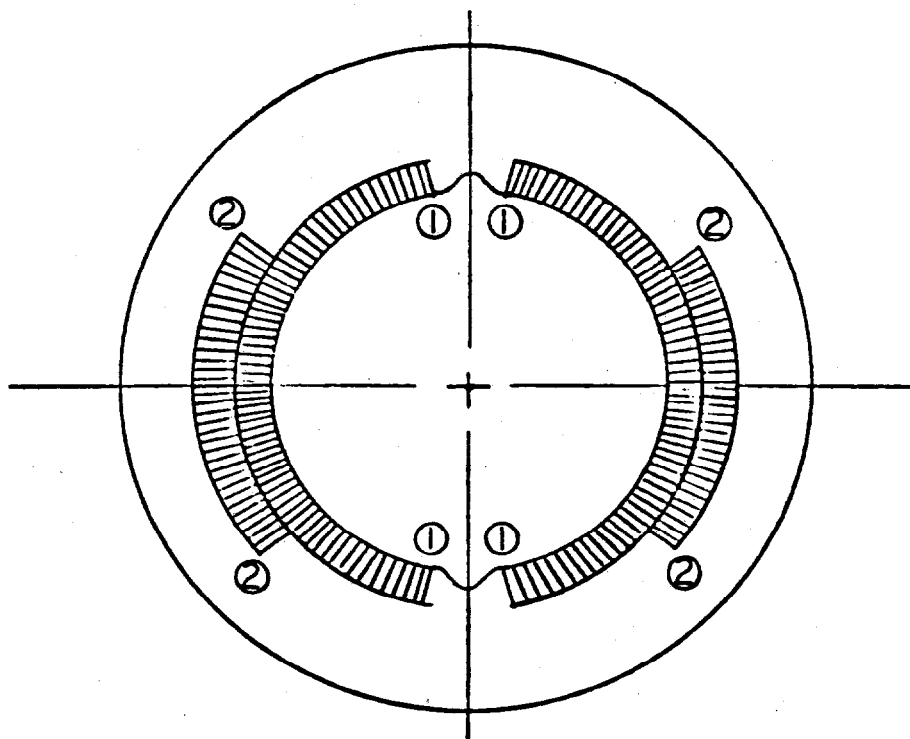coil of the shape shown below (Figure 4).

Figure 4. Coil Cross Section

The structure is designed in such a way that the stainless steel shim stock can be inserted before collaring, at the points labeled ① and ② . Thus the angles of the coil blocks can be changed by small amounts at will.

Consider the harmonic structure of such a coil. The calculated movements in $\delta B/B$ at 1" are given below (integrated through the magnet).

$$b_2 = 0$$

$$b_4 = 1.1 \times 10^{-4}$$

$$b_6 = 4.4 \times 10^{-4}$$

$$b_8 = -12.1 \times 10^{-4}$$

$$b_{10} = 3.6 \times 10^{-4}$$

$$b_{12} = -0.8 \times 10^{-4}$$

$$b_{14} = .07 \times 10^{-4}$$

These coefficients give a $B(x)/B_0$ (integrated through magnet) as a
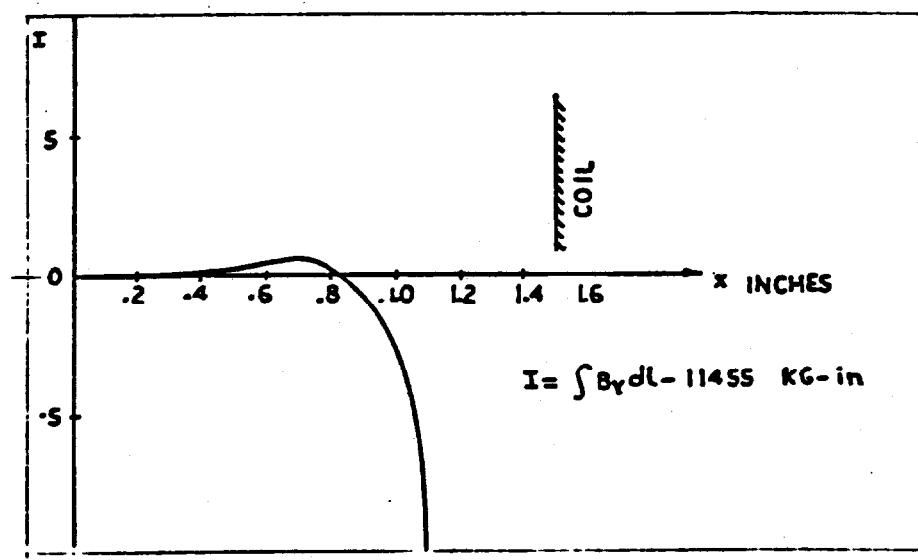
function of x as shown in Figure 5.

Figure 5. Variation of the Integral of B Through
the Magnet as a Function of Radius

With a little work it can be shown that for small changes of the
coil shape only the multipoles below the 14-pole will change. Thus,
if the coil is not exactly circular, but perhaps a little elliptical
or square, or some other shape, the higher multipoles which are deter-
mined by the Fourier components of the current block corners will be
nearly the same as in the correct coil shape. However, the decapole
terms and below will be different and there are eight places shims can
be inserted into the coil structure to modify these components.

Thus we arrive at an important point. If the factory is repro-
ducible, a coil can be built, measured, and the next one corrected to
have a uniform field without having to produce a coil whose absolute
dimensions are known. This process will leave a small random fluctua-
tion in the central field, B_0, but this is very small and the orbit
distortions can be corrected by the horizontal correction elements

that are necessary in any event.

We now present some data gathered over the last two years. Over 170 coil assemblies have been constructed during the development of the coil fabrication technique. Some of these coils are suitable for accelerator tests after their insertion into a cryostat. Some are being used in rather extensive systems tests to be described later, and many of the rest will be useful for beam transport. To get some idea of the overall quality of these magnets, for use in beam transport systems, it may be said that the random errors have always been small enough so that a single pass through 740 such randomized magnets leaves the phase space inside $\pm\frac{1}{2}$" essentially an undisturbed ellipse.

The last major hurdle was to close the room temperature feedback loop, which was done in January 1979. In the meantime the magnets have been shortened by one foot in order to accommodate shielding in the quadrupole cryostats which will help protect the dipole coils from stray beam at injection and extraction. Since April 1979 the new series of 21' magnets has been underway. On the basis of what we have learned it is expected that "Accelerator quality" magnets will be produced. The factory has been operated at a level of five magnets per week for short test periods and should be capable of 10/week. The main problems expected are in the quality control area.

MAGNET MEASUREMENTS

We begin by presenting data obtained in vertical dewar tests of the collared coils.[7] The yoke and cryostat are not yet assembled and only measurements of training, peak field, ramp rate dependence, change in radius of the coil, azimuthal motion of the wire, transfer constant, and residual field due to persistent currents are measured.

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Figure 6 shows the training history of one of the recent coils, #167, and Figure 7 gives the B dependence of the quench point. A typical load line and maximum quench point are given in Figure 8. With the iron, the peak field point is 1.1 B_0 at the key of the inner coil, and without iron the high field point is at the inner turn at the very end of the coil. The end turns are spaced out slightly to reduce the field at the end.

Now to examine the statistics of a number of coils we show the following three histograms. Figure 9 shows the number of quenches to reach 95% of I_{max}, and Figure 10 shows the percent of expected short sample current that the coil achieves. The short sample curve of each reel of wire is measured after being received from the manufacturer. Finally, Figure 11 shows the distribution of peak quench currents obtained.

The ramp rate dependence of the coils is determined by both the heat generated during ramping as well as by the cooling. The coils initially were wound with Stay-Brite-coated wire. Subsequently it has been determined that eddy current losses in the coil package were too high with such good contact between the strands of wire. Consequently we are now using Ebonol-(copper oxide) coated strands and the losses are essentially all due to hysteresis.

COIL LOSSES

	Ebonol	Stay-Brite
Hysteresis	200J	200 J
Eddy Current	~20J	160-560 J

The above numbers are for the following ramp:

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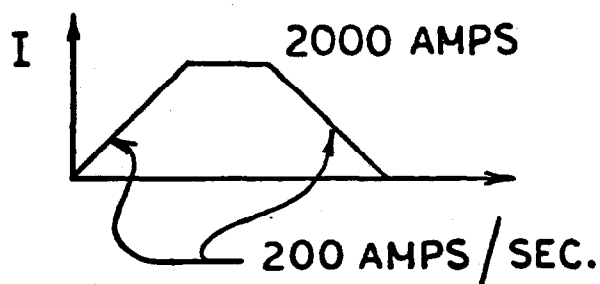
The collars must contain a force in the x direction of 6000 lb/inch, which tends to blow the coil apart. Fatigue studies were made of the collaring system and a lifetime in excess of 10^8 cycles is now expected. Figure 12 shows the radial deflection as a function of coil current. It is accurately parabolic and a histogram of the deflections of 23 magnets is given in Figure 13. There are other elastic motions of the wire. These have been studied and their net effect on the field shape is well within the level of the correction circuits. It is worth noting that the persistent currents generate a rather strong sextupole field (~10 gauss) which must be corrected and in general, in superconducting magnets, there must always be dynamic correction elements which are under program control and with a magnitude of a few $\times 10^{-4}$.

After the magnet coil is assembled in its cryostat[8] it is given a complete set of precision magnetic tests in the Magnet Test Facility.[9] This Facility consists of six test stands where a magnet may be connected to power and refrigeration, and a 1500 watt refrigerator capable of cooling the system. Each magnet is vacuum tested, tested cryogenically, trained, its ramp rate dependence measured as well as the energy loss per cycle at various B's. Finally, a complete set of dc and ramped field harmonics is measured at eleven different currents. The $\int B \cdot dl$ is measured by a combination of NMR and Hall probes that are moved through the magnet automatically by the computer. This complete
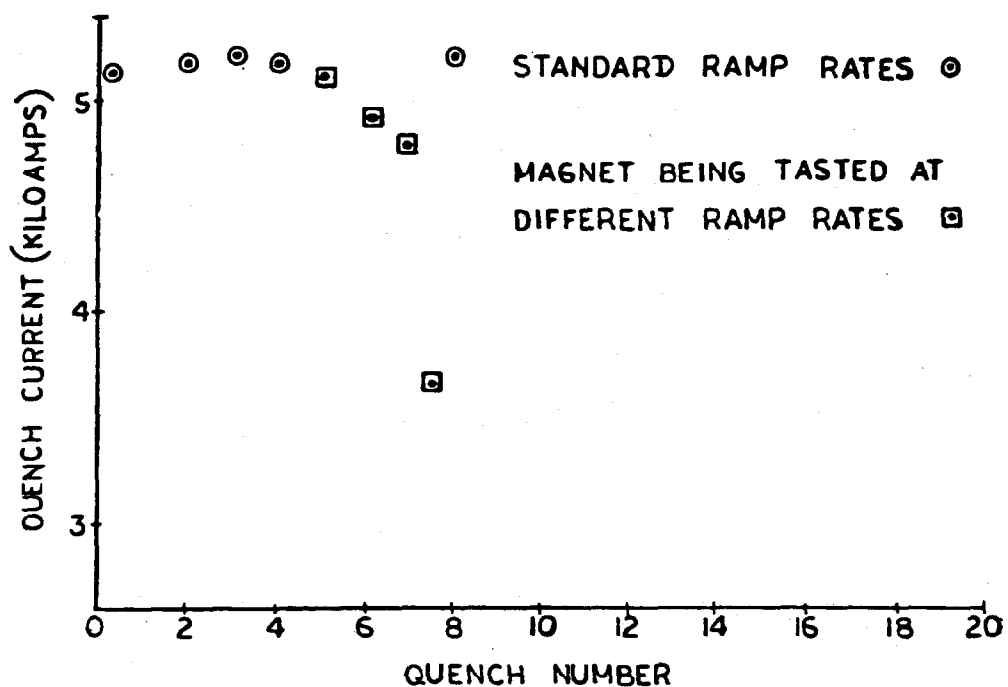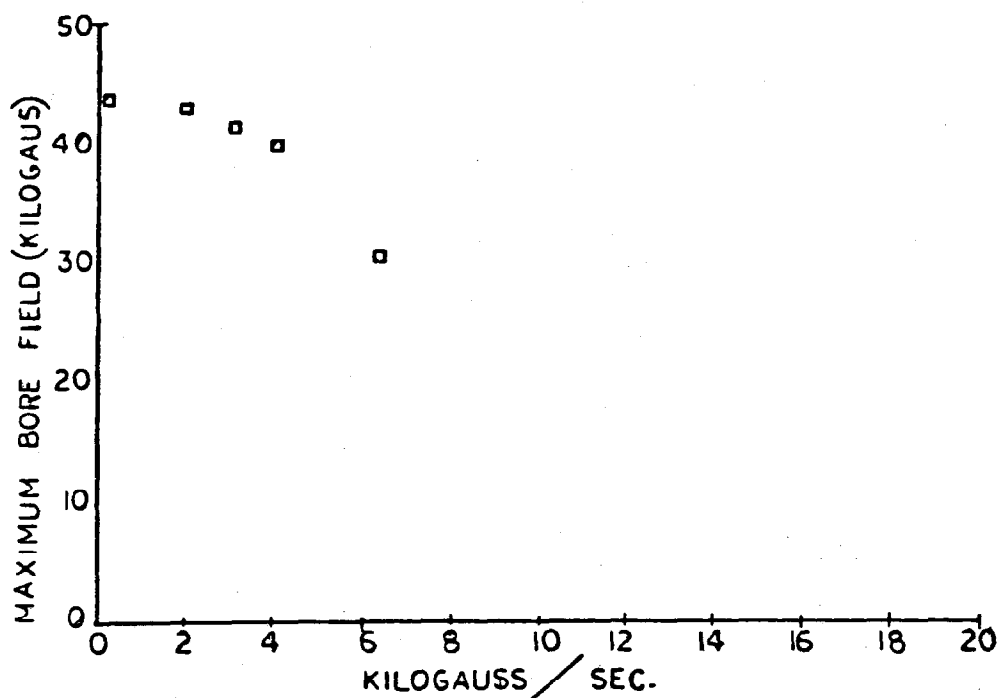
Figure 6. Training – #167

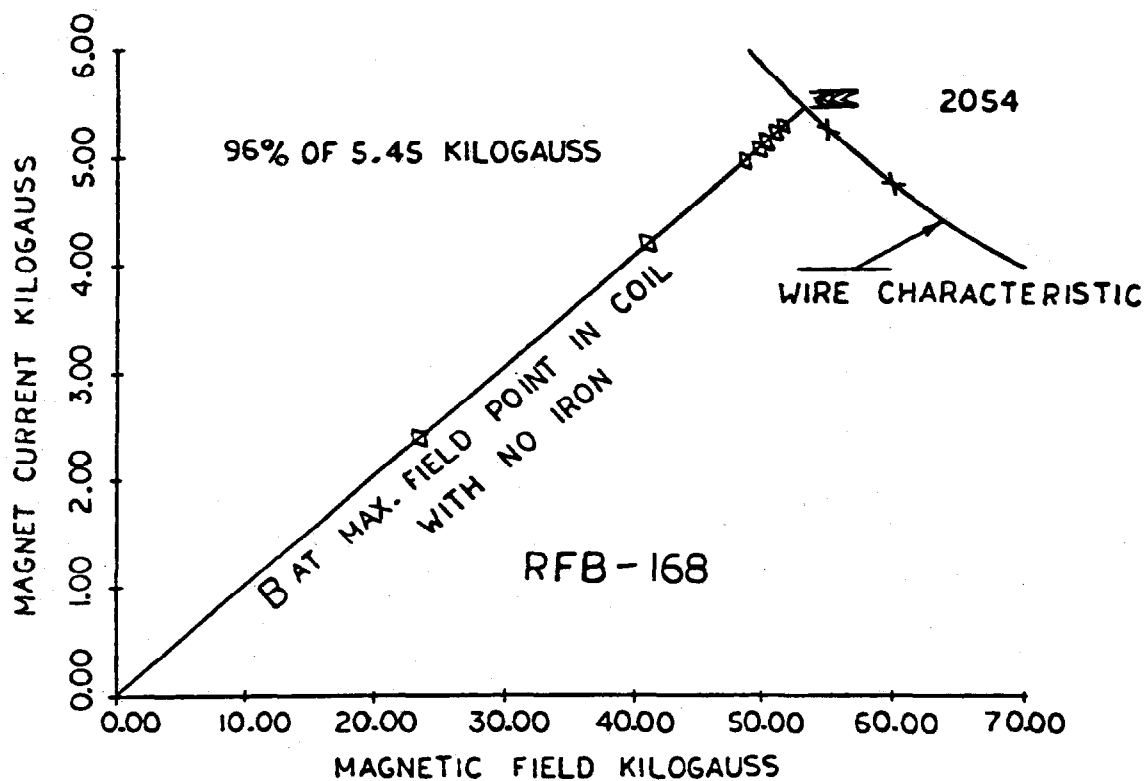Figure 7. B Curve

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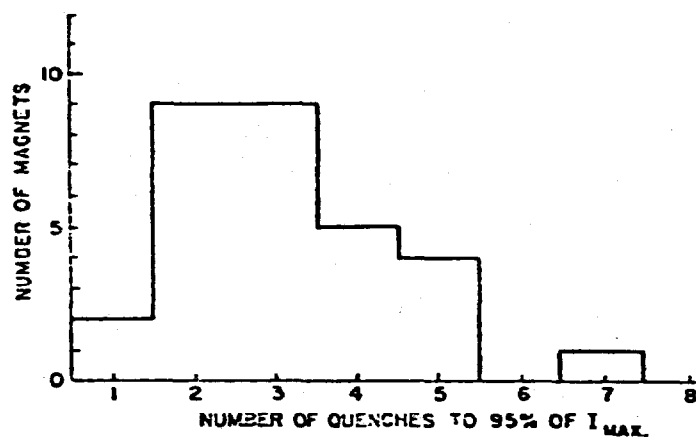Figure 8.   Load Line and Short Sample Limit
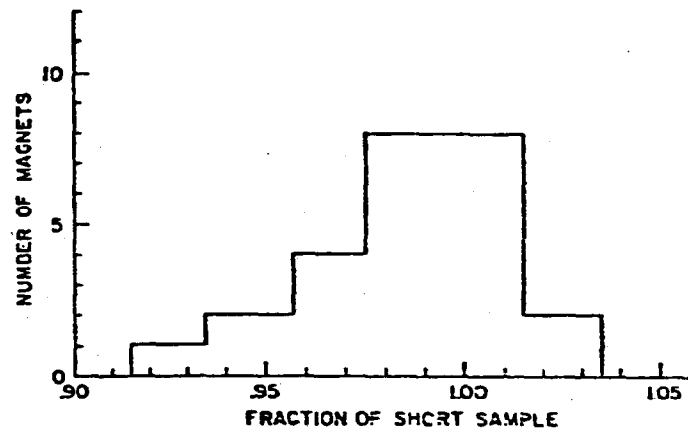

Figure 9.   Train Current Distribution

Figure 10.   Distribution of Final Training Current
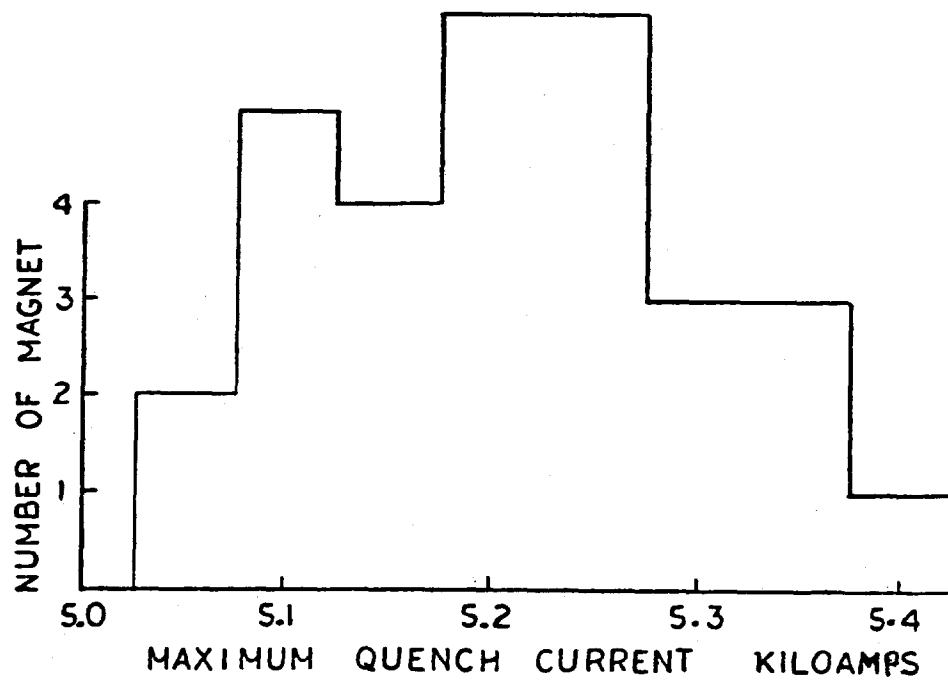
as a Fraction of Short Sample Limit

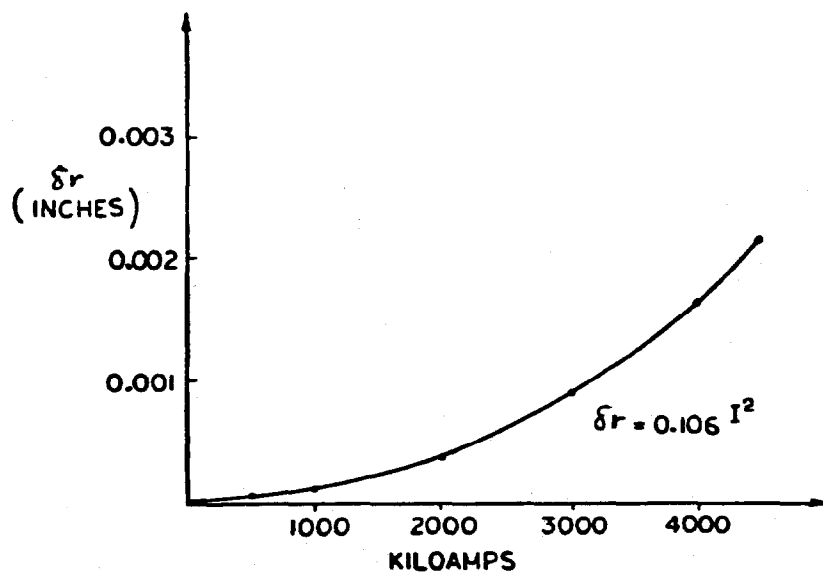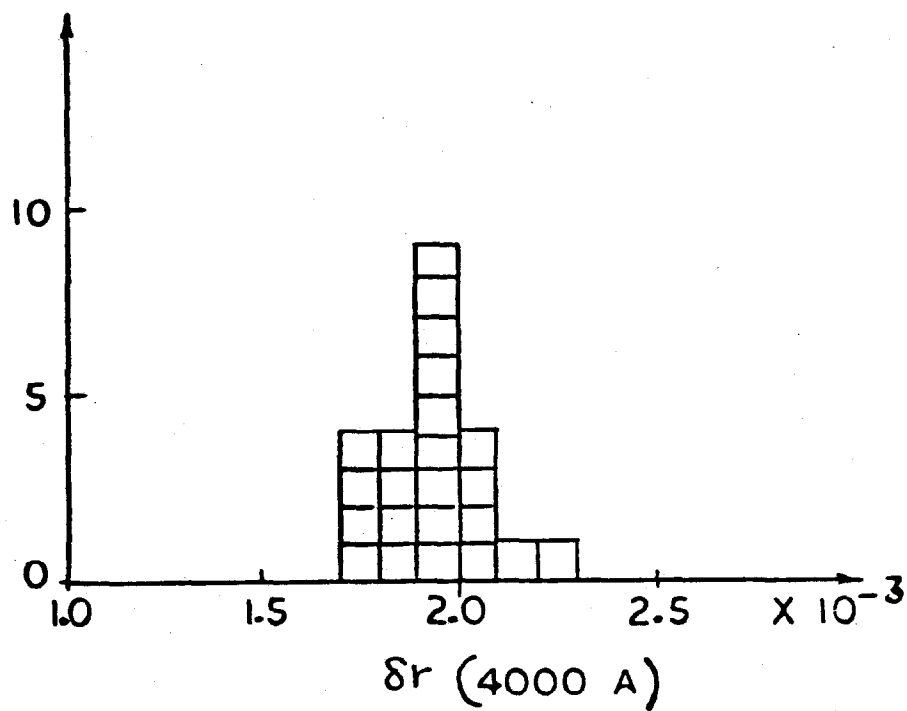Figure 11.   Distribution of Max. Quench Current

Figure 12. Radial Deflection vs Magnet Current

Figure 13. Distribution of δr at 4000 Amps

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set of data plus assembly data is stored on a DISC File as permanent data for each magnet. So far about 40 magnets have had a complete set of measurements made, and almost 80 have had partial measurements. We can now examine some of this data.

Figure 14 shows a histogram of the quench current at 200 A/sec. The effects of different types of conductors can be seen in Figure 15a. Figure 15b shows a histogram of the magnet effective length. Some identifiable structure changes took place and account for some of the spread in the histogram.

Both the normal and skew harmonics are measured up to 30-pole. The following Table lists the harmonics averaged over 24 magnets.

TABLE I

K	Pole	Average		Limits	
		A(k)	B(k)	A(k)	B(k)
1	Quadrupole	1.78 ± 3.18	-0.16 ± 1.65	±2.5	±2.5
2	Sextupole	0.58 ± 0.89	-9.20 ± 6.15	±1.6	±6.4
3	Octupole	-0.16 ± 1.72	0.33 ± 0.71	±4	±4
4		0.11 ± 0.62	3.69 ± 1.87		
5		-0.18 ± 0.48	0.33 ± 0.40		
6		-0.26 ± 0.38	3.41 ± 0.49		
7		0.15 ± 0.34	-0.01 ± 0.36		
8		0.21 ± 0.67	-12.96 ± 0.41		
9		0.36 ± 0.45	0.06 ± 0.45		
10		-0.00 ± 0.45	4.42 ± 0.37		
11		-0.16 ± 0.34	0.08 ± 0.37		
12		0.00 ± 0.37	-1.13 ± 0.36		
13		0.06 ± 0.42	-0.04 ± 0.53		
14	30-pole	-0.01 ± 0.40	-0.01 ± 0.33		

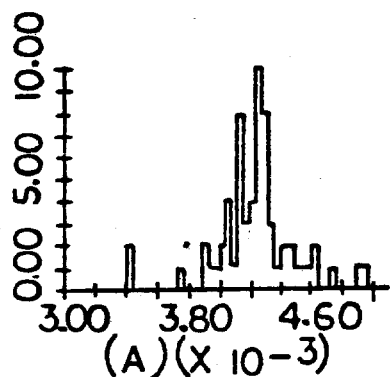All units $\frac{\delta B \cdot \times 10^4}{B}$ at 1^4

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Figure 14.   Distribution of I_Q
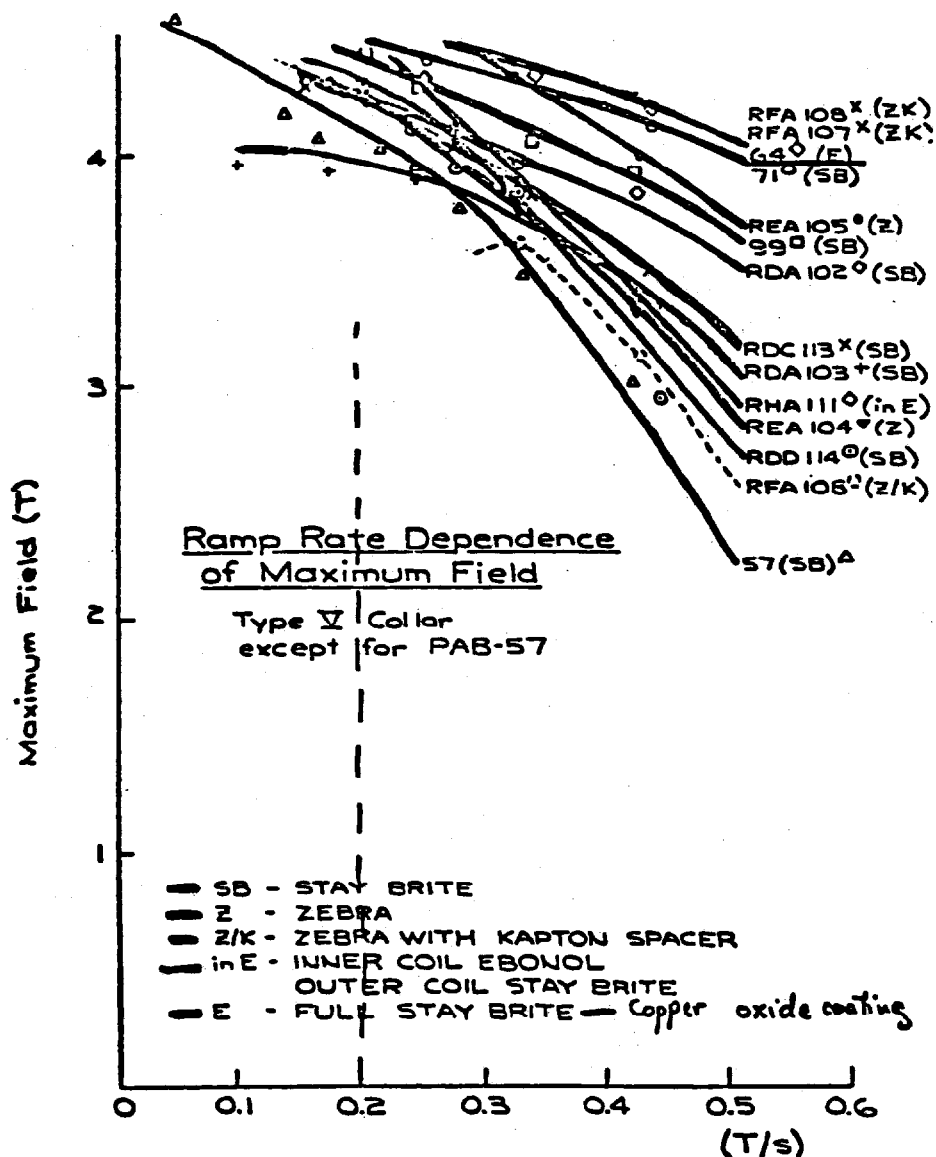
at $\dot{I}$ = 200 A/sec

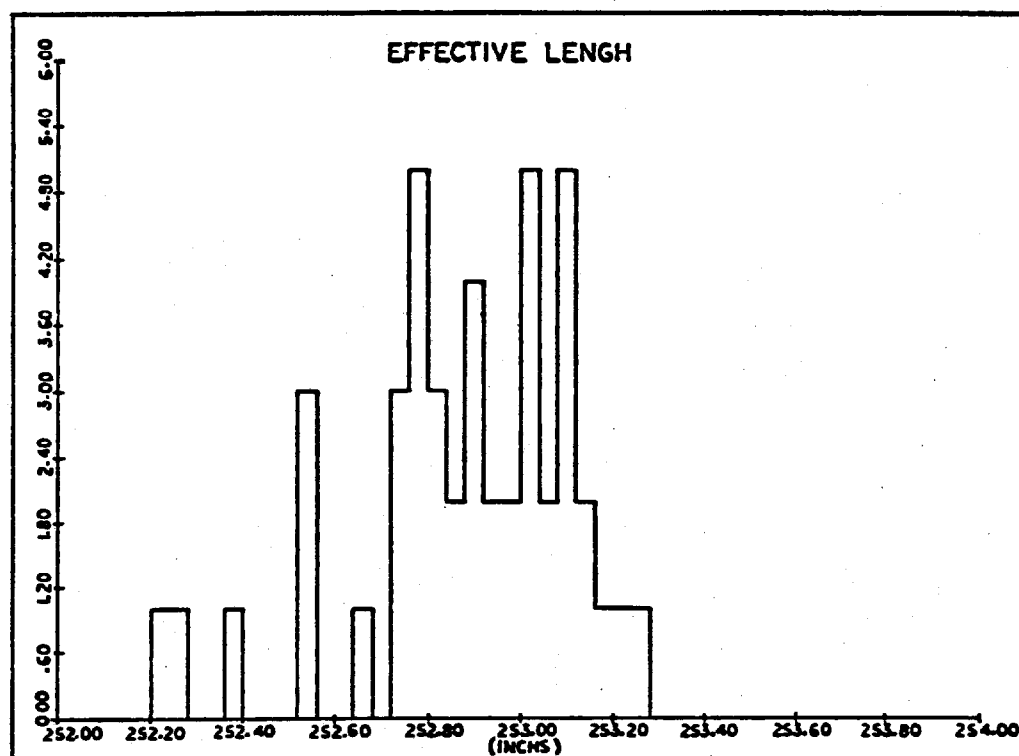Figure 15a.   Ramp Rate Dependence of Magnets in Cryostats

Figure 15b. Effective Length at 2 T

All of the a_n and the odd b_n should be missing in an ideal magnet. These terms therefore give some indication of the random errors gener- ated during coil fabrication. The even b_n are permitted and their val- ues are listed on page 9, along with the design value. It is seen that above the decapole the design values agree well with the desired ones. The sextupole and decapole are not correct. These will be corrected by adjusting the shims at the keys. The line labeled "Limits" indi- cates the results of theoretical studies on the acceptable limits for various multipoles in the Tevatron. This study is not yet finished and work is still in progress. Limits on multipoles not listed will shortly be specified.

Small effects due to coil motion and persistent currents in the superconductor cause the multipole movements to be current dependent.

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Eddy current effects are also present in the cable strands. All of
these effects mainly show up in the sextupole moment. Eddy currents in
the Ebonol winding are too small to measure, but Figure 16 shows the
hysteresis in the sextupole moment b_2. Dynamic corrections are planned
to cancel out this variation. The results of many other measurements
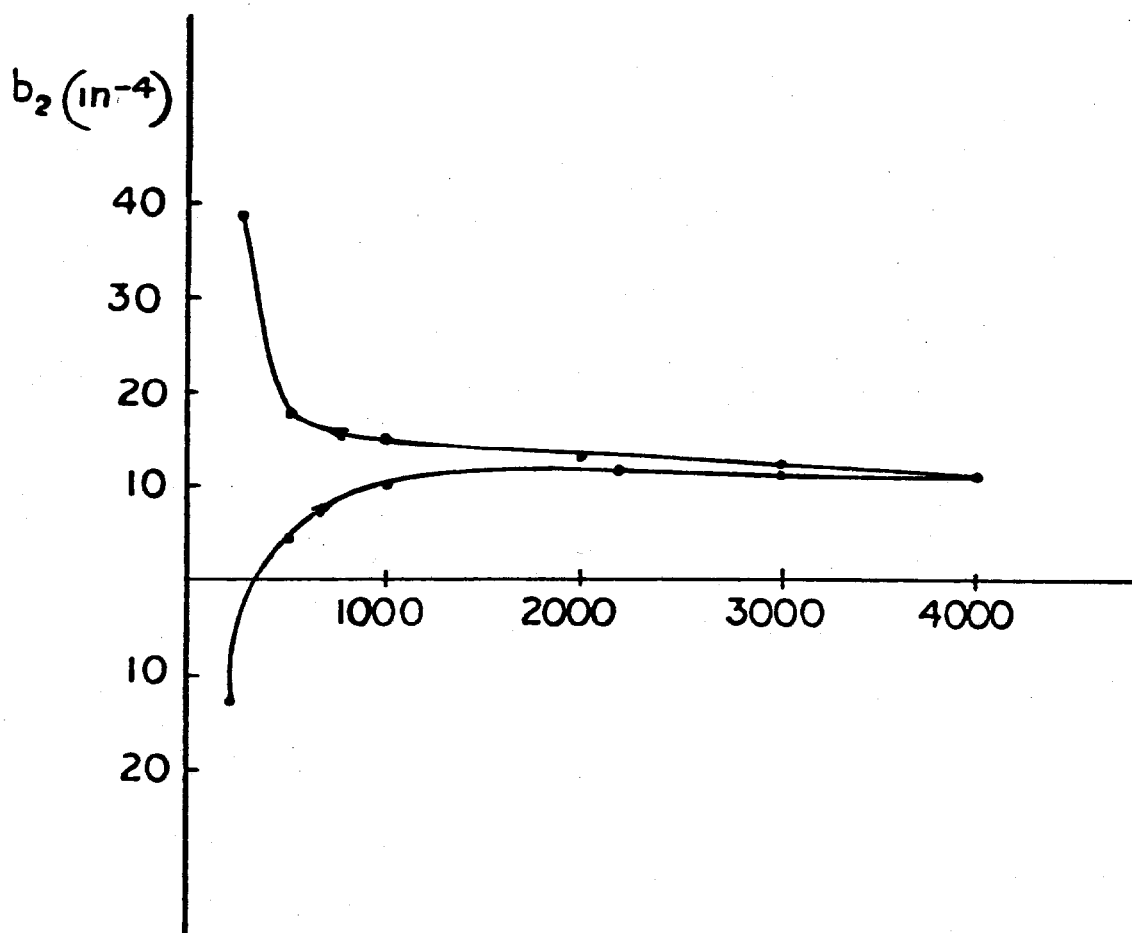are given in Reference 9.

Figure 16.   Sextupole Moment vs Magnet Current

BEHAVIOR OF STRING OF MAGNETS

At present tests on strings of magnets are being intensively
studied. Three types of tests have been conducted.

First, strings of four to eight magnets have been cooled, pulsed to full field and their behavior under quench conditions studied.[10] These tests were above ground and no beam was involved and their primary option has been to develop the quench protection system and a prototype power supply. Cryogenic tests have also been made, which verify the initial calculations of the static heat load of a magnet being about 6 watts.

Figure 17 shows the enthalpy of the coil itself, the coil plus collars, and the helium. It is seen that the helium serves as an energy "ballast" at operating temperature and that a full energy quench with all of the energy uniformily deposited throughout only the coil would raise the coil temperature to no more than 100°K. The main function of the heaters that are fired when a quench is detected is to bring as much of the coil as possible into active energy absorption. The crosses show the temperature actually recorded in the magnet structure gas at about 2-3 minutes after a quench. It is seen that some fraction of the energy is carried off by the helium. This is not yet quantitatively understood and further work is in progress to study these effects.

Figure 18a, b, shows the $\int I^2 dt$ and the pressure in the cryostat vs the current in the magnets for induced quenches in a string of four magnets.

In the near future the string of four magnets will be increased to eight and then 16 -- which is close to half of a "cryogenic string".

In addition to tests above ground, three series of tests have been carried out with beams of protons passing through the magnets.[11] We reproduce here a curve from the study by Cox which shows the variation of the number of protons at 400 GeV hitting the magnets that will
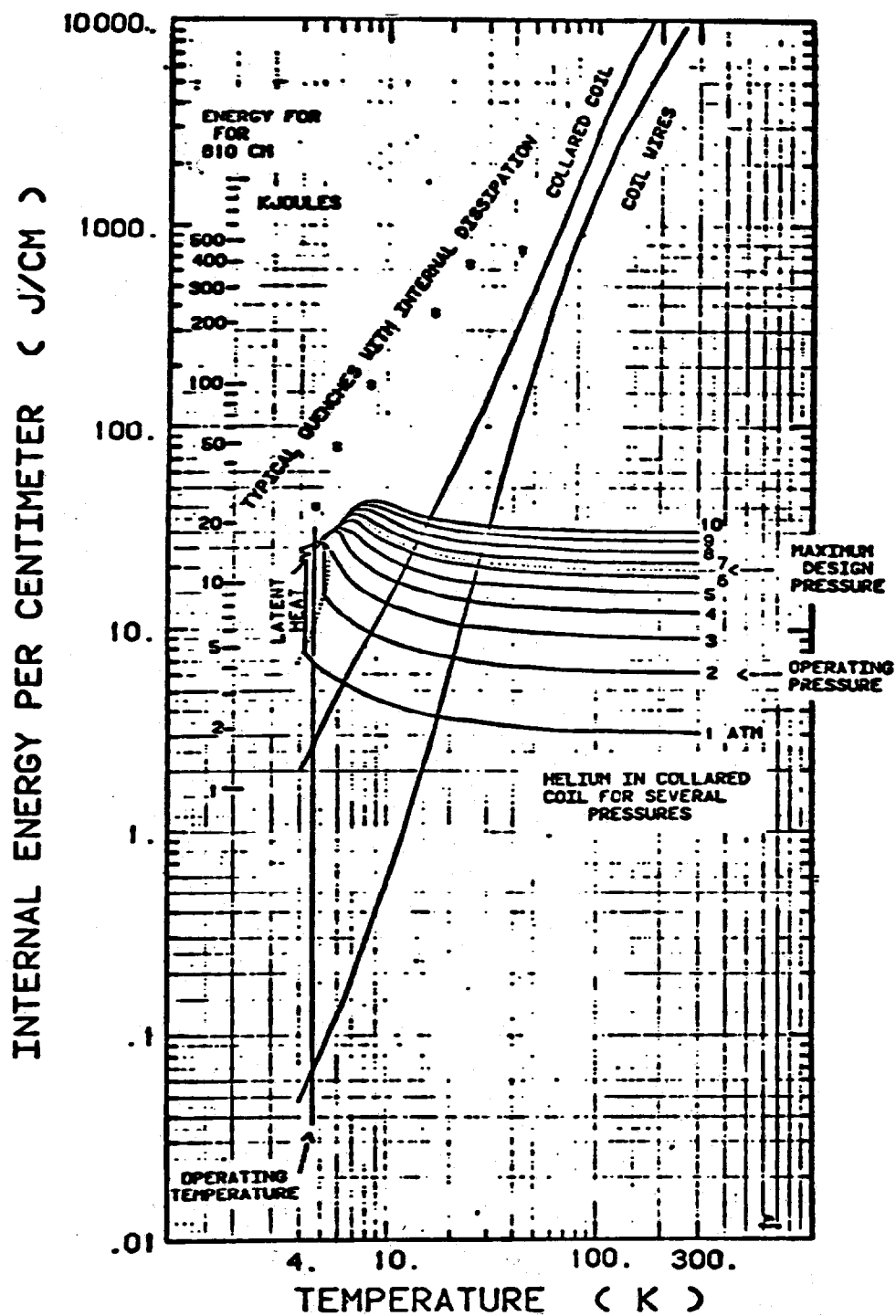
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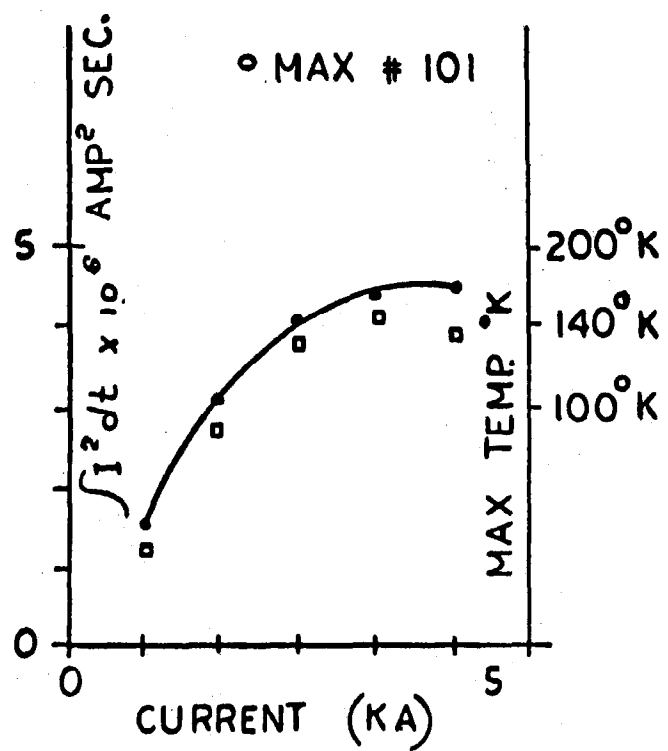Figure 17. Enthalpy of Coil and Magnet Structures
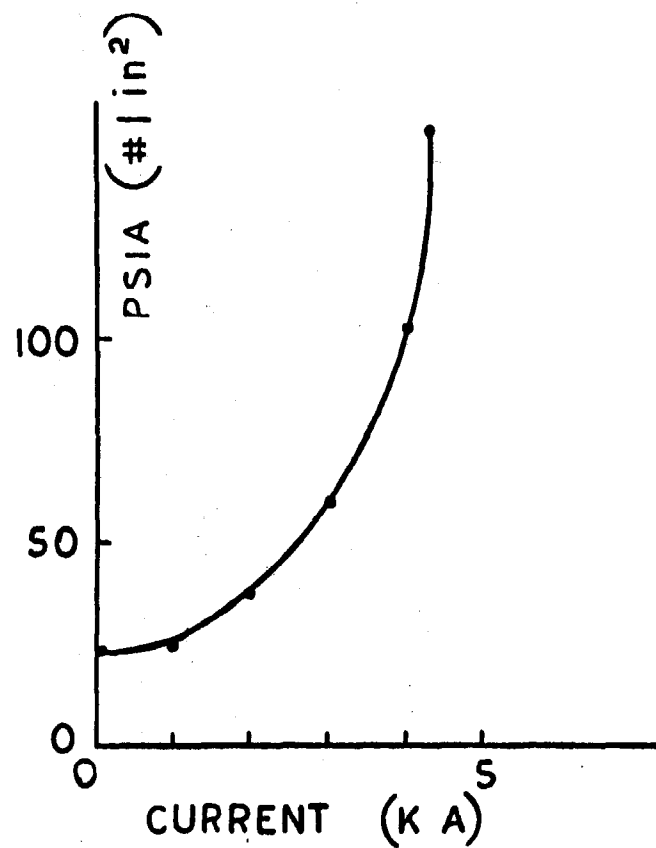
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Figure 18a.

Figure 18b.

$\int I^2 dt$ and the Pressure in the Cryostat vs the Current in the Magnets

cause a quench vs the magnet current. The magnet has a no beam quench limit of about 4000 A. Calibration of the beam indicated that at 3500 A in the magnet, 4 mW/g for slow extraction, or about 1 mJ/g per pulse (1 msec) for fast extraction will cause quenching of the magnets. Extensive studies of technique for shielding the magnets during extraction have been carried out,[12] and techniques are being developed so that the Tevatron can provide both slow as well as fast extracted beam.

Finally, a string of 24 magnets and their associated quadrupoles are installed in the Main Ring tunnel and are being cooled by a satellite refrigerator. (See Figure 18.) Beam was first passed through the string at 90 GeV in January 1979. Much experience has been gained in learning how to install and cool Doubler magnets under the actual conditions that must finally be faced. At the low injection energy it was very pleasant to discover that the string of magnets would recover from a beam induced quench in less than 30 sec. These studies are being continued, but full field studies will not be carried out until tests above ground on smaller strings of magnets have been studied in greater detail.

SUMMARY

The program at Fermilab is now about ready to go into production of accelerator-quality magnets suitable for installing in the final Tevatron ring. It is felt that the major problems of producing high quality, rugged, vacuum-tight and cryogenically acceptable magnets have been overcome. It is hoped that a major step toward applying superconductivity to accelerator magnets has been mastered and that the way is opened to applying these techniques to still higher energy machines in the future.
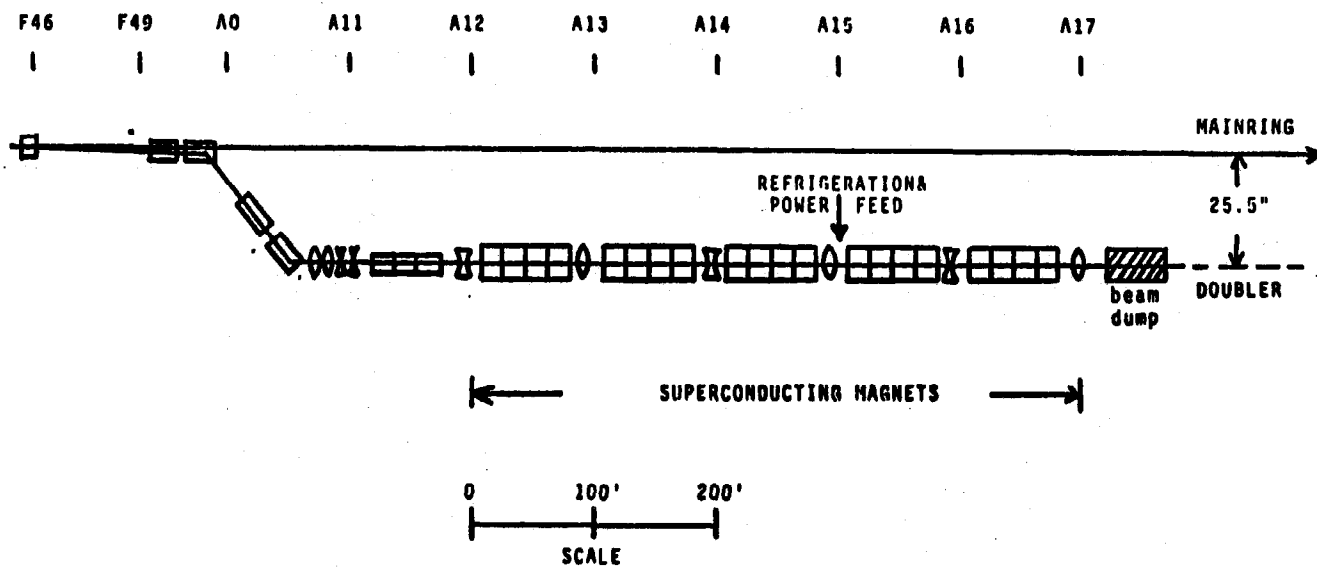
F46 F49 A0 A11 A12 A13 A14 A15 A16 A17

MAINRING

REFRIGERATION&
POWER FEED

25.5"

beam
dump

DOUBLER

SUPERCONDUCTING MAGNETS

0   100'   200'

SCALE

Figure 19. String Magnets

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TM-880

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